Large Area Electronic Skin

Ravinder Dahiya, *Senior Member, IEEE*

Bendable Electronics and Sensing Technologies (BEST) Group,

Electronics and Nanoscale Engineering Research Division, University of Glasgow, G12 8QQ, UK

Email - Ravinder.Dahiya@glasgow.ac.uk

***Abstract*— Technological advances have enabled various approaches for developing artificial organs such as bionic eyes, artificial ears, and lungs etc. Recently electronics (e-skin) or tactile skin has attracted increasing attention for its potential to detect subtle pressure changes, which may open up applications including real-time health monitoring, minimally invasive surgery, and prosthetics. The development of e-skin is challenging as, unlike other artificial organs, tactile skin has large number of different types of sensors, which are distributed over large areas and generate large amount of data. On top of this, the attributes such as softness, stretchability, and bendability etc., are difficult to be achieved as today's electronics technology is meant for electronics on planar and stiff substrates such as silicon wafers. This said, many advances, pursued through "More than Moore" technology, have recently raised hope as some of these relate to flexible electronics and have been targeted towards developing e-skin. Depending on the technology and application, the scale of e-skin could vary from small patch (e.g. for health monitoring) to large area skin (e.g. for robotics). This invited paper presents some of the advances in large area e-skin and flexible electronics, particularly related to robotics.**

I. Introduction

Electronic or tactile skin has attracted significant attention recently for its potential use in numerous applications including bestowing lost sensory feelings to amputees [1, 2], providing critical sensory feedback to robots, and enabling non-invasive means for detection and monitoring of chronic diseases etc.. Large area tactile skin in robotics and prosthetics is also needed for safe physical interaction with real-world objects. For example, a robot could manipulate fragile objects effectively, or help the elderly with greater safety, if its actions were based on feedback such as pressure or temperature coming from its body parts while it was physically in contact with the object or person in question.

Tactile skin plays a fundamental role in providing action-related information such as sticking and slipping; vital control parameters for manipulation/control tasks such as grasping; and estimation of contact parameters such as contact force, soft contact, hardness, texture, temperature *etc*. Tactile skin could also be indispensable for numerous medical diagnoses and surgical applications through haptic interfaces. For example, to feel the presence of tumors in underlying body tissue, the visual feedback of laparoscopic instruments is often insufficient; inserting a tool with tactile as well as visual feedback might prove more useful [3-5]. The typical curvy 3D surfaces in above applications require realizing electronics and sensors on non-conventional substrates such as plastics and paper, which are bendable and can conform to various shapes [6].

The requirements from above applications are sufficient to define e-skin. In context with robotics and prosthetics the e-skin should have various types of distributed sensors (e.g. pressure, temperature etc.) and should have distributed computing to process the distributed sensory data [3]. The e-skin should be able to conform to various curved surface and therefore the electronics should be bendable or conformable. The soft and conformable e-skin will enable superior handling of objects, much as the human skin. Thus, the e-skin or tactile skin may be defined as a structure with multiple sensors such as touch and temperature sensors, displays, energy scavengers, and electronics etc. distributed and integrated on a flexible or bendable substrates or stack of foils [1, 7].

The functionalities such as conformability or stretchability of electronics are not possible with today's silicon based planar electronics. For this reason, a number of fabrication strategies including printing of semiconducting materials are being explored [8]. In terms of materials, thus far the research in the field has largely focussed on organic semiconductors, which results in slower electronic devices due to inherent low charge career mobility. However, many emerging applications such as internet of things, smart cities, cognitive robotics, and smart cities, etc. require fast computation and communication responses (e.g. wireless communication above radio frequency range), and therefore, high mobility materials such as single crystal silicon, and graphene, etc. have been explored recently for flexible electronics [9]. As far as graphene is concerned, it has emerged as an interesting material for flexible electronics because it is ultra-flexible, strong and can provide high-performance electronics, owing to its superior electrical properties [10]. However, the zero-band gap of graphene is currently a significant challenge for graphene based electronics and circuits. Nonetheless, excellent properties of graphene can be exploited to develop multiple functionalities such as sensors or optoelectronic devices. As for electronics, with careful integration strategy, the Si based electronics (in particular the CMOS chips) could still be used to read or drive the devices [11]. A variety of approaches and designs are being pursued to develop an effective e-skin. Some of these approaches are described here.

This paper is organized as follows: Brief description of various approaches for developing parts of e-skin is given in section II and the section III summarized the key concluding points.

II. Various Approaches

A. E-skin using Off-the-Shelf components

Early attempts to obtain bendable electronic skin followed the flexible printed circuit board route. Here, off-the-shelf sensing and electronic components are soldered to bendable

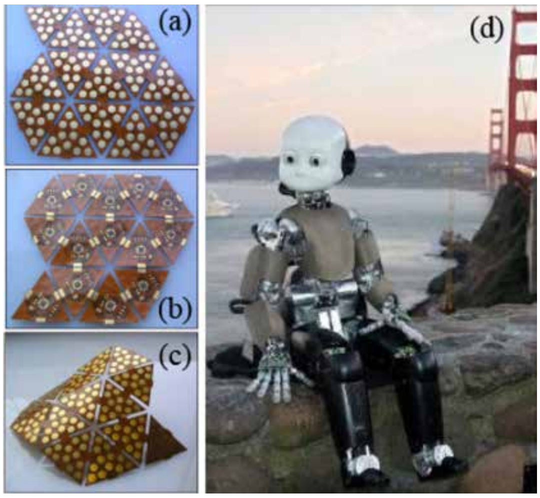
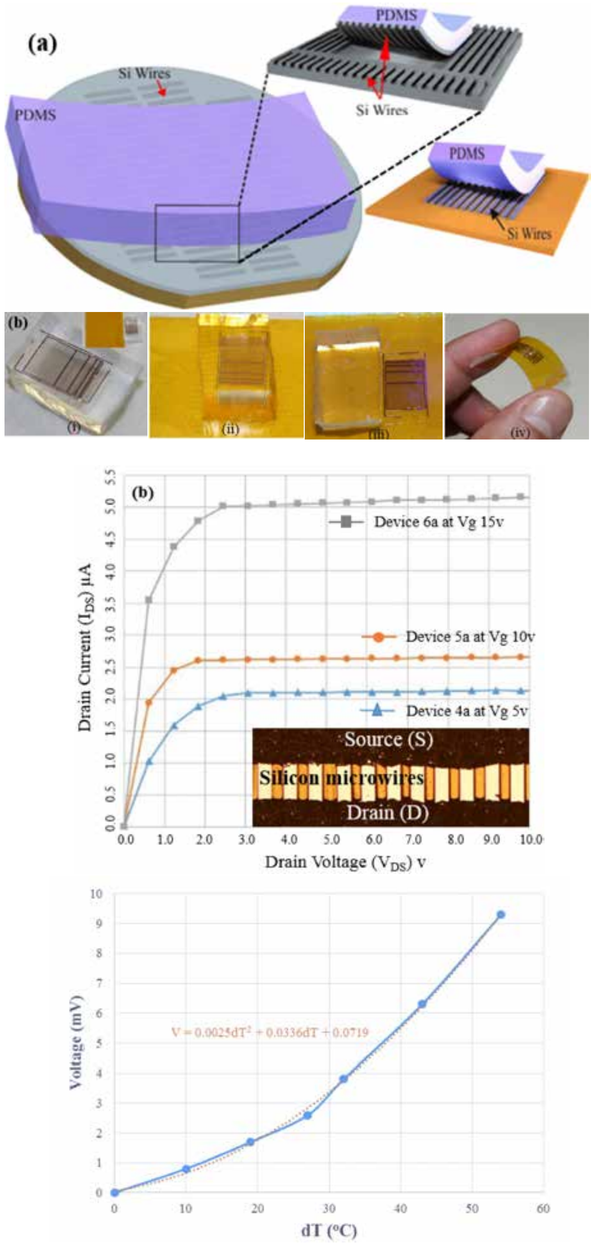


Fig 1: The example of large area tactile skin with off-the shelf electronic/sensing components. (a) Top/Front side of the flexible printed circuit board tactile skin. The bottom electrodes of capacitive sensors present on top can be seen. (b) The back side of tactile skin where off-the-shelf electronics components such as capacitance to digital converter chip are soldered. (c) the image showing bendability of tactile skin, and (d) the humanoid robot 'iCub' with tactile skin covering most of its body [9].

printed circuit boards [5, 12]. These solutions are akin to having mechanically integrated but otherwise distinct and stiff sub-circuit islands of off-the-shelf electronic components, connected to one another by metal interconnects. This approach was also adopted by the European Commission funded project roboskin. The semi-rigid flexible PCB based skin patches conform to surfaces with large curvature such as arms of a humanoid robot 'iCub' (Fig. 1) [9]. Further extension of this approach is affected by off-the-shelf electronics, which are not bendable. Nonetheless, the flexible PCB based tactile skin served some of the urgent robotic needs. The large area implementation of tactile skin has opened new research areas in robotics, whereby multiple contact points or areas contact with the objects is exploited to plan robotic movements.

B. Printing of Electronic and Sensing Components

Another approach for obtaining e-skin (and flexible electronics, in general) involves printing of active/passive sensing and electronics components on the flexible substrates [8, 13, 14]. There are numerous examples where this type of approach has been used to obtain both active and passive electronic components. The approaches for obtaining active electronics and sensing components directly on flexible substrates include printing or transferring the basic building blocks (e.g. nanowires and ribbons of Silicon, Graphene etc.) to flexible substrates. The micro-/nano-structures such as wires of single-crystal silicon are promising building blocks for realizing high performance nano- to macro scale FETs [15]. The viability of this approach for flexible electronics has been demonstrated with microwires [16-20], as shown in Fig. 2. The method involves fabricating single-crystal silicon microstructures using standard photolithography and dry-wet etching, followed by transferring ordered or oriented arrays of these microstructures to ultra-flexible receiver substrate (polyimide) using PDMS as carrier. This procedure



(d)

Fig 2: (a) Transfer printing process of Si microwires on flexible substrates. (b) Results from various stages of transfer printing, (c) Output of MISFET devices made of multiple Si multiwires at different gate voltages. (d) Output of thermoelectric energy harvestor from alternate *p*-type and *n*-type doped Si microwires on PET substrate [18].

overcomes the thermal budget challenges.

C. Ultra-thin Flexible Chips

The solid state sensors or electronic chips that are normally realized on planar and brittle silicon wafers cannot be integrated well on curved surfaces such as body of a humanoid robot. The lack of bendability leads to underutilization of many novel schemes. This was the case for POSFET (Piezoelectric Oxide Semiconductor Field Effect Transistor) tactile sensing chips, which we developed in past [21-26]. Lack of conformability had been one drawback of otherwise sensitive POSFET chips in terms of their effective usage in applications such as robotic skin. The research on ultra-thin flex-chip (Fig. 3) is a step towards obtaining flexible POSFET tactile sensing chips and in

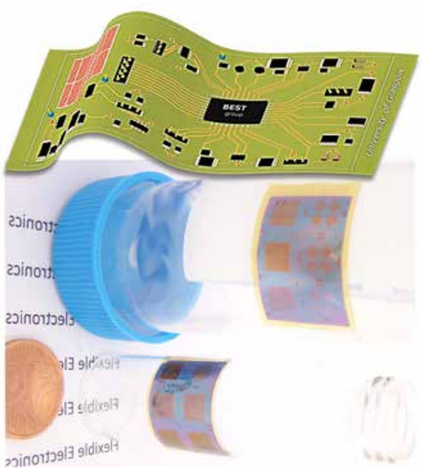


Fig.3: (*top*) Flex-chip on flex integration concept. (*bottom*) The ultra-thin flex-chips placed on the cylinders with $18mm$ and $30mm$ diameters [27].

general for compact flexible electronics [27]. In brief, the fabrication involves thinning of wafer by back-side chemical etching. The flex-chip approach has potential to open up new avenues for heterogeneous integration of organic and inorganic semiconductor based electronics as flex-chip can the provide high-performance integrated electronics needed for many solutions such as organic semiconductors based displays.

III. Conclusion

There has been a growing interest in realizing multifunctional active and passive electronic components on nonconventional substrates such as soft plastics and even paper to obtain flexible, foldable and stretchable electronic systems for applications such as wearable electronics, displays and robotic skin etc. This latest research paper in the field, presented in this paper, highlights the key direction, particularly for large area e-skin based on high-performance flexible electronics. The e-skin approaches presented here are based on: (a) off-the shelf electronic and sensing components on flexible PCBs, (b) printing of passive components directly on flexible substrates, (c) printing silicon in new forms (e.g. nano/microwires), and (d) ultra-thin silicon chips (flex-chips).

Acknowledgement

This work supported by the Engineering and Physical Sciences Research Council (EPSRC) Engineering Fellowship for Growth (EP/M002527/1), EPSRC First Grant (EP/M002519/1), and in part by the European Commission under Grant PITN-GA-2012-317488-CONTEST. Author is thankful to the members of his Bendable Electronics and Sensing Technologies (BEST) group for their support.

References

[1] R. Dahiya, "Epidermal Electronics: Flexible Electronics for Biomedical Application," in *Handbook of Bioelectronics - Directly interfacing electronics and biological systems*, S. Carrara and K. Iniewski, Eds., ed: Cambridge University Press, 2015, pp. 245-255.

[2] N. Yogeswaran, W. Dang, W. T. Navaraj, D. Shakthivel, S. Khan, E. O. Polat*, et al.*, "New materials and advances in making electronic skin for interactive robots," *Adv. Robotics,* vol. 29, pp. 1359-1373, 2015.

[3] R. Dahiya and M. Valle, *Robotic Tactile Sensing – Technologies and System*. Dordrecht: Springer, 2013.

[4] R. Dahiya, P. Mittendorfer, M. Valle, G. Cheng, and V. Lumelsky, "Directions Towards Effective Utilization of Tactile Skin -- A Review," *IEEE Sensors Journal,* vol. 13, pp. 4121 - 4138, 2013.

[5] R. Dahiya, G. Metta, M. Valle, G. Sandini, "Tactile Sensing - From Humans to Humanoids," *IEEE Trans Robotics,* vol. 26, pp. 1-20, 2010.

[6] A. Nathan, A. Ahnood, M. T. Cole, S. Lee, Y. Suzuki, P. Hiralal*, et al.*, "Flexible electronics: the next ubiquitous platform," *Proceedings of the IEEE,* vol. 100, pp. 1486-1517, 2012.

[7] http://www.contest-itn.eu/. *CONTEST - Collaborative Network for Training in Electronic Skin Technology*.

[8] S. Khan, R. Dahiya, L. Lorenzelli, "Technologies for Printing Sensors and Electronics over Large Flexible Substrates: A Review," *IEEE Sensors Journal,* vol. 15, pp. 3164-3185, 2015.

[9] R. Dahiya, W. T. Navaraj, S. Khan, E. Polat, "Developing Electronic Skin with Sense of Touch," *Inform. Display,* vol. 31, pp. 6-10, 2015.

[10] E. O. Polat, O. Balci, N. Kakenov, H. B. Uzlu, C. Kocabas, and R. Dahiya, "Synthesis of Large Area Graphene for High Performance in Flexible Optoelectronic Devices," *Scientific Reports,* vol. 5, 2015.

[11] H. Heidari, E. Bonizzoni, U. Gatti, F. Maloberti, R. Dahiya, "CMOS Vertical Hall Magnetic Sensors on Flexible Substrate," *IEEE Sensors J.,* vol. PP, pp. 1-1, 2016 (in press).

[12] G. Cannata, R. S. Dahiya, M. Maggiali, F. Mastrogiovanni, G. Metta, and M. Valle, "Modular skin for humanoid robot systems," presented at the 4th Int. Conference on Cognitive Systems (CogSys), Zurich, 2010.

[13] S. Khan, S. Tinku, L. Lorenzelli, R. Dahiya, "Flexible Tactile Sensors Using Screen-Printed P(VDF-TrFE) and MWCNT/PDMS Composites," *IEEE Sensors J.,* vol. 15, pp. 3146-3155, 2015.

[14] S. Khan, W. Dang, L. Lorenzelli, R. Dahiya, "Flexible Pressure Sensors Based on Screen-Printed P(VDF-TrFE) and P(VDF-TrFE)/MWCNTs," *IEEE Trans. Semicond. Manufact.*, vol. 28, pp. 486-493, 2015.

[15] S. Khan, N. Yogeswaran, W. Taube, L. Lorenzelli, R. Dahiya, "Flexible FETs using ultrathin Si microwires embedded in solution processed dielectric and metal layers," *J. Micromech. Microengg,* vol. 25, p. 125019, 2015.

[16] D.-H. Kim, J.-H. Ahn, W. M. Choi, H.-S. Kim, T.-H. Kim, J. Song*, et al.*, "Stretchable and Foldable Silicon Integrated Circuits," *Science,* vol. 320, pp. 507-511, 2008.

[17] R. S. Dahiya, A. Adami, C. Collini, L. Lorenzelli, "Fabrication of Single Crystal Silicon Mirco-/Nanostructures and Transferring them to Flexible Substrates," *Microelectr. Engg,* vol. 98, pp. 502-507, 2012.

[18] S. Khan, R. Dahiya, L. Lorenzelli, "Flexible Thermoelectric Generator Based on Transfer Printed Si Microwires,," in *44th European Solid-State Device Research Conference*, Venice, Italy, 2014, pp. 1-4.

[19] R. Dahiya, G. Gottardi, N. Laidani, "PDMS residues-free micro/macrostructures on flexible substrates," *Microelectronic Engineering,* vol. 136, pp. 57-62, 3/25/ 2015.

[20] S. Khan, L. Lorenzelli, R. Dahiya, "Flexible MISFET Devices From Transfer Printed Si Microwires and Spray Coating," *IEEE J. Electron Dev. Soc.,* vol. 4, pp. 189-196, 2016.

[21] R. Dahiya, D. Cattin, A. Adami, C. Collini, L. Barboni, M. Valle*, et al.*, "Towards Tactile Sensing System on Chip for Robotic Applications," *IEEE Sensors J.,* vol. 11, pp. 3216-3226, 2011.

[22] R. Dahiya, G. Metta, M. Valle, A. Adami, L. Lorenzelli, "Piezoelectric oxide semiconductor field effect transistor touch sensing devices," *Applied Physics Letters,* vol. 95, pp. 034105-034105-3, 2009.

[23] R. Dahiya, A. Adami, L. Pinna, C. Collini, M. Valle, L. Lorenzelli, "Tactile Sensing Chips With POSFET Array and Integrated Interface Electronics," *IEEE Sensors J.,* vol. 14, pp. 3448-3457, 2014.

[24] R. Dahiya, A. Adami, C. Collini, and L. Lorenzelli, "POSFET Tactile Sensing Arrays using CMOS Technology," *Sensors and Actuators - A,* vol. 202, pp. 226-232, 2013.

[25] A. Adami, R. S. Dahiya, C. Collini, D. Cattin, and L. Lorenzelli, "POSFET touch sensor with CMOS integrated signal conditioning electronics," *Sensors and Actuat.s A,* vol. 98, pp. 502-507, 2012.

[26] R. S. Dahiya, "Piezoelectric Tactile Sensors," in *Wiley Encyclopedia of Electrical and Electronics Engineering*, J. Webster, Ed., ed New Jersey: John Wiley & Sons, Inc., 2015.

[27] R. S. Dahiya and S. Gennaro, "Bendable Ultra-Thin Chips on Flexible Foils," *IEEE Sensors Journal,* vol. 13, pp. 4030-4037, 2013.